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This Final Report describes our program in studies of (laminar/turbulent) stability and transition in non-equilibrium-chemistry flows characteristic of those on the forebodies of hypersonic vehicles. The configuration best modelling a hypersonic vehicle is an elliptic cone. Specifically, we investigated and optimized a Parabolized Navier-Stokes solution for the basic-state flow past a sharp elliptic cone including the region between the wall and the shock. We formulated the Parabolized Stability Equations for 3-D flows.

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STABILITY OF HYPERSONIC BOUNDARY - LAYER FLOWS

Final Report

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ABSTRACT

This Final Report describes our program in studies of (laminar/turbulent) stability and transition in non-equilibrium-chemistry flows characteristic of those on the forebodies of hypersonic vehicles. The configuration best modelling a hypersonic vehicle is an elliptic cone. Specifically, we investigated and optimized a Parabolized Navier-Stokes solution for the basic-state flow past a sharp elliptic cone including the region between the wall and the shock. We formulated the Parabolized Stability Equations for 3-D flows.

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1. Introduction

This Final Report describes our program in studies of (laminar/turbulent) stability and transition in non-equilibrium-chemistry, bounded flows characteristic of those on the forebodies of hypersonic vehicles. In this Report, Section 2 contains a list of accomplishments. Section 3 contains a summary of the work.

2. Technical Accomplishments

In the past 3 years, 2 students have been supervised, 15 publications have been written or are in preparation, and 9 talks and lectures have been given.

Publications

"Transition Correlations in 3-D Boundary Layers," H.L. Reed and T.S. Haynes, *AIAA Journal,* Volume 32, Page 923, 1994.

"Linear Disturbances in Hypersonic, Chemically Reacting Shock Layers," G.K. Stuckert and H.L. Reed, *AIAA Journal.*, Volume 32, Number 7, Page 1384, 1994.

"Linear Stability Theory Applied to Boundary Layers," H.L. Reed, W.S. Saric, and D. Arnal, *Annual Review of Fluid Mechanics*, Volume 28, 1996.

"CFD Validation Issues in Transition Modelling," H.L. Reed, T.S. Haynes, and W.S. Saric, submitted to *AIAA Journal.*.

"Numerical Investigation Nonlinear Saturation of Crossflow-Dominated Boundary Layers Using PSE," T.S. Haynes and H.L. Reed, submitted to *Journal of Fluid Mechanics*.

"Investigation of PSE Initial Conditions for Crossflow-Dominated Boundary Layers," T.S. Haynes and H.L. Reed, to be submitted to *Journal of Fluid Mechanics.*

"Spatial Direct Numerical Simulations," H.L. Reed, to be submitted to *Progress in Aerospace Sciences*.

"Direct Numerical Simulation of Transition: The Spatial Approach," H.L. Reed, *Invited Paper*, AGARD Course in Transition Prediction and Modelling, AGARD Report No. 793, VonKarman Institute and Madrid, March 1994.

"Use of Transition Correlations for Three-Dimensional Boundary Layers within Hypersonic Flows," I.J. Lyttle and H.L. Reed, *AIAA-95-2293, 26th AIAA Fluid Dynamics, Plasma Dynamics, and Lasers Conference*, San Diego, June 19-22, 1995.

"Use of Transition Correlations for Three-Dimensional Boundary Layers within Hypersonic, Viscous Flows," I.J. Lyttle and H.L. Reed, *Second Symposium on Transitional and Turbulent Compressible Flows, 1995 Joint ASME/JSME Fluids Engineering Conference*, Hilton Head, August 1995.

"Computations in Nonlinear Saturation of Stationary Crossflow Vortices in a Swept-Wing Boundary Layer," T.S. Haynes and H.L. Reed, *AIAA 34th Aerospace Sciences Meeting and Exhibit, AIAA-96-0182*, January 1996.

"CFD Validation Issues in Transition Modelling," T.S. Haynes, H.L. Reed, and W.S. Saric, *Invited Paper*, *AIAA-96-2051*, Special Session on Verification and Validation: Uncertainties and Special Panel on Quantification of CFD Uncertainties, 27th AIAA Fluid Dynamics Conference, New Orleans, June 17-21, 1996.

“Drag Prediction and Transition in Hypersonic Flow,” H.L. Reed, W.S. Saric, R. Kimmel, S. Schneider, and D. Arnal, *Invited Paper*, AGARD Interpanel (FDP&PEP) Symposium on "Future Aerospace Technology in Service to the Alliance", Paris, France, April 14-18, 1997

“Drag Prediction and Transition in Hypersonic Flow,” H.L. Reed, R. Kimmel, S. Schneider, and D. Arnal, *Invited Paper, AIAA-97-1818*, Snowmass, June 1997.

“Role of Direct Numerical Simulations in Transition Modelling,” H.L. Reed, *Invited Paper*, First AFOSR DNS/LES Conference, New Orleans, August 1997.

Presentations

"Direct Numerical Simulation of Transition: The Spatial Approach," H.L. Reed, *Invited Paper*, AGARD Course in Transition Prediction and Modelling, AGARD Report No. 793, VonKarman Institute and Madrid, March 1994.

"Usc of Transition Correlations for High-Speed Three-Dimensional Boundary Layers," I.J. Lyttle and H.L. Reed, *Bulletin of the American Physical Society*, Volumc 39, Number 9, Page 1913, November 1994.

"Use of Transition Correlations for Three-Dimensional Boundary Layers within Hypersonic Flows," I.J. Lyttle and H.L. Reed, *AIAA-95-2293, 26th AIAA Fluid Dynamics, Plasma Dynamics, and Lasers Conference*, San Diego, June 19-22, 1995.

"Use of Transition Correlations for Three-Dimensional Boundary Layers within Hypersonic, Viscous Flows," I.J. Lyttle and H.L. Reed, *Second Symposium on Transitional and Turbulent Compressible Flows, 1995 Joint ASME/JSME Fluids Engineering Conference*, Hilton Head, August 1995.

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"CFD Validation and Verification Questions in Transition Modelling," T.S. Haynes, H.L. Reed, and W.S. Saric, *Invited Paper*, *AIAA-96-2051*, Special Session on Verification and Validation: Uncertainties and Special Panel on Quantification of CFD Uncertainties, 27th AIAA Fluid Dynamics Conference, New Orleans, June 17-21, 1996.

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“Drag Prediction and Transition in Hypersonic Flow,” H.L. Reed, R. Kimmel, S. Schneider, and D. Arnal, *Invited Paper, AIAA-97-1818*, Snowmass, June 1997.

“Role of Direct Numerical Simulations in Transition Modelling,” H.L. Reed, *Invited Paper*, First AFOSR DNS/LES Conference, New Orleans, August 1997.

Ph.D. Students

T. Haynes, "Nonlinear Stability and Saturation of Crossflow Vortices in Swept-Wing Boundary Layers," completed Fall 1996.

I. Lyttle, "Stability of Hypersonic Flow over an Elliptic Cone," expected Summer 1998.

3. Completed Work

3.1 Introduction

The world over, theorists and experimentalists are investigating the problems associated with hypersonic flight. Much of the current research into hypersonic flight is concentrated in the range of Mach 5 to Mach 15 (Reshotko, 1992). The skin-friction drag and heat-transfer rates of hypersonic vehicles depend on the state of the boundary layer, that is, whether it is laminar or turbulent. Moreover, the performance of the engine depends on the state of the boundary layer at the inlet. But the characteristics of transition at these speeds are not well understood. Transition *is* known, however, to be highly dependent on the details of the flowfield.

The current conceptional design of the hypersonic vehicle includes a forebody which could be modeled as a sharp cone with an elliptical cross-section. It is this geometry, at zero angle-of-attack, that is of interest to this study. The boundary layers associated with this geometry are three-dimensional. As Reed & Saric (1989) point out, three-dimensional boundary layers are susceptible to crossflow instabilities, as well as streamwise instabilities. In fact, these crossflow instabilities are often the dominant mechanisms responsible for transition, and, in discussions on upper-atmosphere hypersonic transition experiments, much consideration has been given to the minimization of three-dimensional effects (Kimmel, 1994).

Hypersonic flows are more complicated than subsonic and supersonic flows for some of the following reasons. 1) At hypersonic speeds, the gas often cannot be modeled as perfect because the molecular species begin to dissociate due to aerodynamic heating. In fact, sometimes there are not enough intermolecular collisions to support local chemical equilibrium and a nonequilibrium-chemistry model must be used. 2) The bow shock is very close to the edge of the boundary layer and must be included in the calculations. 3) The boundary layers on the forebody are highly 3-D. All of these effects must be included in predictions of transition.

3.2 Chemically Reacting Basic-State Flow

The purpose of this investigation is to examine the three-dimensional nature of boundary layers found on sharp cones of elliptical cross section. Initially, the basic state is solved using a finite-difference formulation of a set of Parabolized Navier-Stokes (PNS) equations. The set of PNS equations used is that derived by Lubard & Helliwell (1974). The finite-difference algorithm used to solve these PNS equations descends from the scheme derived by Tannehill et al. (1982). Since the boundary layer occupies a substantial fraction of the shock layer at hypersonic speeds, these equations are transformed into a coordinate system where the basic-state bow shock is a boundary of the computational domain. We recognize that for complex flowfields with strong viscous/inviscid interaction, reduced forms of the equations of motion do not provide solutions

accurate enough for transition studies, and it is necessary as a next step to solve either the full Navier-Stokes (NS) or Thin-Layer-Navier-Stokes (TLNS) equations. We are in the process of formulating and completing this activity.

Code Optimization

We have already made major improvements to increase the computational efficiency of the PNS scheme. The reason we did this was in preparation for the addition of the nonequilibrium-chemistry terms and the extension to either the full Navier-Stokes or Thin-Layer-Navier-Stokes formulations, which (we knew from our previous experience) would significantly increase the magnitude of the problem.

For the Cray Y-MP and the Cray C-90, there is a facility called vectorization, whereby the CPU can act like an assembly line. This allows many operations to be performed at one time, increasing the number of arithmetic operations performed without increasing the amount of CPU time used. To achieve vectorization, certain rules must be followed concerning the order of operations, etc. In many cases, this requires major changes in the algorithm and corresponding changes in the code. For this research, vectorization is possible and is exploited. The most computationally intensive parts of the program involve the solution of block-tridiagonal systems of equations. The majority of the optimization effort was placed here.

Step 1. A routine was written to invert matrices on the diagonal to exploit their structure.

Step 2. Major input and output routines use binary files instead of ASCII files.

Step 3. The block-tridiagonal systems are solved plane-by-plane instead of line-by-line.

Step 4. The algorithm was analyzed to remove code which was not necessary.

A simple representative run of the code was performed to gauge the effectiveness of the optimization. The speed improvements do not correspond exactly to the improvements in time because Step 4. was carried out over the entire course of the optimization. The top speed of one CPU of the Cray Y-MP is 338 MFLOPS. According to the staff at CEWES, this is a theoretical limit that is rarely approached. However, they are supportive of efforts to achieve such goals.

	Code Speed (MFLOPS)	CPU Time to complete (s)
Before optimization	10.4	207
After Step 1	40.9	33
After Step 2	60.7	22
After Step 3	163.6	8

SIGNIFICANCE One obvious benefit of this effort is the major savings of CPU resources for this project. Further more complex and resource intensive codes written in support of this research will be written using the principles learned in this simple initial effort. This will result in more efficient use of a valuable, limited resource to solve a critical national problem.

Chemistry

Qualitative as well as quantitative differences in the transition of the shock layer on a forebody can be observed when the effects of finite-rate chemical reactions are included. We are following the studies of stability on a cone of circular cross-section by Stuckert & Reed (1994) who used a five-component model for dissociated air: O_2, N_2, NO, N, and O. Only the effects of dissociation were considered; those of ionization were not. The mixture was also assumed to be one of ideal gases in thermal equilibrium. The viscosity used to determine the viscous stress tensor was computed using the mixture laws of Brokaw (1958). The translational thermal conductivity was computed similarly, whereas the internal thermal conductivity was determined as described in Hirschfelder (1957). The molar fluxes were computed using the multicomponent diffusion model described by Curtiss & Hirschfelder (1949), but only diffusion due to concentration gradients was included - diffusion due to pressure and temperature gradients and body forces was not. Finally, the law of mass action was used to compute the molar rate of production of each species assuming that they participate in the elementary reactions:

$$O_2 + M \leftrightarrow O + O + M$$

$$N_2 + M \leftrightarrow N + N + M$$

$$NO + M \leftrightarrow N + O + M$$

$$N_2 + O \leftrightarrow NO + N$$

$$O + NO \leftrightarrow N + O_2$$

where M is a collision partner (any of the species present in the mixture) which transfers energy in a reaction.

The thermophysical data needed for the analysis were taken from a variety of sources. Collision cross section data for the transport properties were found in Biolsi & Biolsi (1983), Biolsi (1988), Capitelli & Devoto (1973), Capitelli & Ficocelli (1972), Cubley & Mason (1975), Levin et al. (1987, 1988), Monchick (1959), and Yun & Mason (1962). Thermodynamic data were taken from Blottner et al. (1971) and Jaffe (1987). Reaction-rate data were found in Camac & Vaughan (1961), Wray (1962), Thielen & Roth (1986), Monat et al. (1978), and Hanson &

Salimian (1984). Reverse reaction-rate constants were computed using the law of detailed balance to express them in terms of the forward-rate and equilibrium constants. For a complete description of the constitutive equations as well as detailed references for the thermophysical data, refer to Stuckert (1991).

Josyula & Shang (1993) at Wright Patterson Air Force Base computed the 2-D steady, basic-state flow over a hemisphere-cylinder at Mach 10-18 Hemisphere-Cylinder. They used an explicit NS formulation with a 5-component chemical non-equilibrium model, comparable to Stuckert & Reed's. However, the objective of their work was to determine the sensitivity of heat-transfer predictions to the temperature model used (single temperature to multi-temperature, Stuckert & Reed used single temperature). They used a 40 x 50 grid on a CRAY XMP, which performed at 3.38E-4 cpu-s/(pt.iteration) and required 20,000 iterations to converge.

At this point we have succcessfully included equilibrium chemistry in the PNS equations. Over the next year, we shall incorporate non-equilibrium chemistry and investigate the effects of (sensitivity to) chemistry (equilibrium and non-equilibrium), as well as formulate and solve either the full Navier-Stokes (NS) or Thin-Layer-Navier-Stokes (TLNS) equations.

3.3 Parabolized Stability Calculations for Transition Prediction

3.3.1 Introduction

In wall-bounded shear layers, transition occurs because of an incipient instability of the basic flow field, which depends intimately on subtle, and sometimes obscure, details of the flowfield. In other words, the wall-bounded shear layer is an open system. Disturbances in the freestream, such as sound or vorticity, enter the boundary layer as steady and/or unsteady fluctuations of the basic state. This part of the process, called receptivity (Morkovin 1969, Reshotko 1984), provides the vital initial conditions of amplitude, frequency, and phase for the breakdown of laminar flow. The recent progress in this area is summarized in Goldstein & Hultgren (1989) and Saric et al. (1994).

Initially these disturbances may be too small to measure and they are observed only after the onset of an instability. The initial growth of these disturbances is described by linear stability theory (LST). Reed et al. (1996) review this subject.

For two-dimensional (2-D) boundary layers, this growth is weak, occurs over a viscous length scale, and can be modulated by pressure gradients, mass flow, temperature gradients, etc. As the amplitude grows, three-dimensional (3-D) and nonlinear interactions occur in the form of secondary instabilities (Herbert 1988, Cowley & Wu 1994, Healy 1995). At this point, disturbance growth is very rapid (now over a convective length scale) and breakdown to turbulence occurs quickly.

3.3.2 Formulation

In this Section we present the formulation for the research. Our main focus is the stability and transition of boundary-layer type flows. For transition analysis using the Parabolized Stability Equation (PSE) approach, equations governing the disturbance are typically solved separately from the basic state. The validity of the basic-state formulations must also be considered since the transition process is known to be sensitive to subtle changes in the basic state. In all cases the numerical accuracy of the basic state must be very high, because the stability and transition results will be very sensitive to small departures of the mean flow from its "exact" shape. The stability of the flow can depend on small variations of the boundary conditions for the basic state, such as freestream velocity or wall temperature. Therefore, basic-state boundary conditions must also be very accurate. See the discussion and examples of Arnal (1994) and Malik (1990).

3.3.3 Parabolized Stability Equations

In recent years the parabolized stability equations (PSE) have become a popular approach to stability analysis owing to their elegant inclusion of the nonparallel and nonlinear effects which are ignored by LST (Herbert 1994; Bertolotti 1990). For linear PSE (LPSE), we consider a single monochromatic wave as the disturbance. The disturbance is decomposed into a rapidly varying "wave function" and a slowly varying "shape function". We accomplish this here with a multiple scales approach.

$$\phi'(x,y,z,t) = \underbrace{\tilde{\phi}(\bar{x},y)}_{shapefunction} \quad \underbrace{\chi(x,z,t)}_{wavefunction} + c.c. \tag{1}$$

where

$$\frac{\partial \chi}{\partial x} = i\alpha(\bar{x}), \quad \frac{\partial \chi}{\partial z} = i\beta, \quad \frac{\partial \chi}{\partial t} = -i\omega \qquad \text{(2)-(4)}$$

This gives the following form for the streamwise derivatives:

$$\frac{\partial \phi'}{\partial x} = \left\{ \frac{1}{R}\frac{\partial \tilde{\phi}}{\partial \bar{x}} + i\alpha\tilde{\phi} \right\} \chi + c.c. \tag{5}$$

$$\frac{\partial^2 \phi'}{\partial x^2} = \left\{ \frac{1}{R^2}\frac{\partial^2 \tilde{\phi}}{\partial \bar{x}^2} + \frac{2i\alpha}{R}\frac{\partial \tilde{\phi}}{\partial \bar{x}} + \frac{i\tilde{\phi}}{R}\frac{\partial \alpha}{\partial \bar{x}} - \alpha^2\tilde{\phi} \right\} \chi + c.c. \tag{6}$$

The shape function $\tilde{\phi}$ and wavenumber α depend on the slowly varying scale $\bar{x}$ while the wave function χ depends on the rapidly varying scale x ($x = R\bar{x}$).

In the PSE approach the second derivative term in (6) is neglected based on physical arguments. Substituting into the disturbance equations gives a system of equations of the form:

$$(L_o + L_1)\tilde{\phi} + L_2 \frac{\partial \tilde{\phi}}{\partial x} + \tilde{\phi} L_3 \frac{\partial \alpha}{\partial x} = 0 \tag{7}$$

Here L_o is the compressible version of the Orr-Sommerfeld operator (provided curvature terms have been neglected), L_1 contains the nonparallel basic state terms, L_2 and L_3 arise due to the nonparallel disturbance terms. The system of equations (7) is parabolic and thus requires boundary and initial conditions. The boundary conditions at $y = 0$ and $y = y_{\max}$ are:

$$\tilde{u} = \tilde{v} = \tilde{w} = \tilde{T} = 0 \tag{8}$$

Notice that setting L_1, L_2, and L_3 equal to zero removes the nonparallel effects and the problem (7)-(8) reduces to the linear parallel problem.

There still remains the matter of the ambiguity in x-dependence between $\tilde{\phi}$ and χ in the decomposition (4). This ambiguity is resolved by imposing any of the normalization conditions

$$\frac{1}{\tilde{u}^*} \frac{\partial \tilde{u}}{\partial x}\bigg|_{y=y_{\max}} = 0 \tag{9}$$

$$\int_0^\infty \tilde{v}^* \frac{\partial \tilde{v}}{\partial x} dy = 0 \tag{10}$$

$$\int_0^\infty \tilde{u}^* \frac{\partial \tilde{u}}{\partial x} dy = 0 \tag{11}$$

where $y_{\max}$ is the location of the maximum magnitude of $\tilde{u}$ (superscript * denotes complex conjugate). Many other normalizations are possible. The normalization ensures that any rapid changes in the streamwise direction will be "absorbed" by the wave function so that the shape function will vary slowly in this direction. This permits us to discard the $O\left(1/R^2\right)$ second derivative term in equation (6). Other normalizations may be used and will give slightly different results. Herbert (1994) is working on an "optimal norm" that will minimize the effect of the PSE approximation on the solution. An integral normalization may be used rather than one applied at $y = y_{\max}$ to avoid the problems associated with shape functions developing multiple maxima.

To complete the problem formulation, initial values of the disturbance flow quantities must be specified at some streamwise location (x_o) for the start of the analysis. If the analysis begins in a region where the initial disturbance amplitudes are small, the LST can be used to obtain these initial conditions.

The nonlinear PSE (NPSE) are derived in a fashion similar to LPSE. Each disturbance quantity is transformed spectrally in the spanwise and temporal directions using

$$\phi'(x,y,z,t) = \sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \underbrace{\tilde{\phi}_{(n,k)}(\bar{x},y)}_{shapefunction} \underbrace{A_{(n,k)}(x) e^{i(k\beta_o z - n\omega_o t)}}_{wavefunction} \tag{12}$$

where

$$\frac{dA_{(n,k)}}{dx} = A_{(n,k)} i\alpha_{(n,k)}(\bar{x}) \tag{13}$$

Here each *mode*, *(n,k),* is considered to be the product of a shape function and a wave function. Because the physical disturbance quantities are real,

$$\begin{aligned} &\alpha_{(n,k)} = -\alpha^*_{(-n,-k)}, \quad \tilde{\rho}_{(n,k)} = \tilde{\rho}^*_{(-n,-k)}, \quad \tilde{u}_{(n,k)} = \tilde{u}^*_{(-n,-k)}, \quad \tilde{v}_{(n,k)} = \tilde{v}^*_{(-n,-k)} \\ &\tilde{w}_{(n,k)} = \tilde{w}^*_{(-n,-k)}, \quad \tilde{T}_{(n,k)} = \tilde{T}^*_{(-n,-k)}, \quad A_{(n,k)} = A^*_{(-n,-k)} \end{aligned} \tag{14}$$

If the basic state is symmetric with respect to the z-direction, the following additional relationships among the disturbance quantities hold:

$$\begin{aligned} &\alpha_{(n,k)} = \alpha_{(n,-k)}, \quad \tilde{\rho}_{(n,k)} = \tilde{\rho}_{(n,-k)}, \quad \tilde{u}_{(n,k)} = \tilde{u}_{(n,-k)}, \quad \tilde{v}_{(n,k)} = \tilde{v}_{(n,-k)} \\ &\tilde{w}_{(n,k)} = -\tilde{w}_{(n,-k)}, \quad \tilde{T}_{(n,k)} = \tilde{T}_{(n,-k)}, \quad A_{(n,k)} = A_{(n,-k)} \end{aligned} \tag{15}$$

Substituting (12) into the disturbance equations gives a system of equations of the form

$$\sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \left\{ (L_o + L_1)\tilde{\phi} + L_2 \frac{\partial \tilde{\phi}}{\partial \bar{x}} + \tilde{\phi} L_3 \frac{\partial \alpha}{\partial \bar{x}} \right\}_{(n,k)} A(n,k) e^{i(k\beta_o z - n\omega_o t)} = N \tag{16}$$

The left hand side consists of the linear terms, while the right hand side consists of the nonlinear terms. The portion in brackets on the left hand side contains the same quantities as in equation (7) for LPSE except the quantities α and $\tilde{\phi}$ now carry the subscripts *(n,k)* identifying them with a particular mode, and ω and β appearing in equation (7) must be replaced with $n\omega_o$ and $k\beta_o$ respectively.

The nonlinearities are quartic for compressible flows where the effect of thermal property fluctuations is considered to be important. For incompressible flows this effect can be neglected leading to only quadratic nonlinearities. In fact, it is reasonable to neglect the cubic and quartic nonlinearites for compressible computations at moderate Mach numbers for cases where their effect on the solution is small. This results in considerable savings since the higher-order nonlinear terms are expensive to compute.

Since a numerical solution to the system (16) is desired, a finite number of modes *(n,k)* must be considered, so the analysis will be restricted to $-N \le n \le N$, $-K \le k \le K$. This is not a severe restriction since we are interested in the downstream evolution of disturbances which consist of only a few modes of finite amplitude at the starting location of the analysis. As the

disturbances propagate downstream they may be amplified and grow to the point where they excite higher modes through nonlinear interactions. Typically, the magnitude of the nonlinear terms is monitored during the numerical solution and modes will be included in the analysis as they become important.

Harmonic balancing of equations (16) for a finite number of modes leads to a system of equations governing each *(n,k)* mode (neglecting higher-order nonlinearities).

$$\left\{(L_o + L_1)\tilde{\phi} + L_2\frac{\partial\tilde{\phi}}{\partial x} + \tilde{\phi}L_3\frac{\partial\alpha}{\partial x}\right\}_{(n,k)} A_{(n,k)} = \sum_{\substack{n=n_2+n_3 \\ |n_2|\le N \\ |n_3|\le N}} \sum_{\substack{k=k_2+k_3 \\ |k_2|\le K \\ |k_3|\le K}} \hat{N}_{(n_2,k_2,n_3,k_3)} \tag{17}$$

The boundary conditions (8) must then be applied for all the modes except the mean-flow distortion (MFD). This mode (*n=k=0*) requires a special boundary condition for the normal velocity at $y = y_{\max}$ to allow for changes in the displacement thickness of the mean-flow profile. The boundary condition $\tilde{v}_{(0,0)} = 0$is then replaced with

$$\frac{\partial\tilde{v}_{(0,0)}}{\partial y} = 0 \tag{18}$$

For problems where there is basic-state *z*-symmetry we need only to solve for 1/4 of the modes ($0 \le n \le N,\ 0 \le k \le K$). The remaining modes will be required during calculation of the nonlinear terms, but they can be computed from the former set of modes by using equations (14)-(15). If no *z*-symmetry exists the computational effort may still be halved using the conditions of realness of the physical disturbance (equations (14)). The nonlinear terms in equation (17) couple the governing equations for all the modes.

Once the continuous PSE have been derived, there are a number of discretizations available. The codes developed by Bertolotti (1990), Stuckert et al. (1993), Stuckert et al. (1994) use Chebyshev collocation in the wall-normal direction and backward-Euler finite differences for the streamwise direction. The backward-Euler finite difference helps damp transients that occur as a result of approximations used to obtain the initial conditions. Bertolotti (1990) uses backward-Euler discretization near the initial location and slowly switches to Crank-Nicolson further downstream. Chang et al. (1991) use either a fourth-order central-difference or compact two-point scheme for derivatives in the wall-normal direction and second-order backward differences (multi-step) in the streamwise direction. Haynes & Reed (1996) use fourth-order central differences for derivatives in the wall-normal direction and backward-Euler discretization in the streamwise direction.

Although the removal of part of the second-derivative terms in the PSE formulation apparently results in a system of parabolic differential equations, there is still some elliptic behavior associated with the upstream propagation of acoustic disturbances. This situation is analogous to the parabolizing procedures used to develop the PNS equations (Anderson et al. 1984). For incompressible formulations the streamwise derivative of the shape function for pressure may be dropped, or a large enough stepsize can be used to "step over" the elliptic region (Malik & Li 1993). The two-dimensional incompressible formulation of Bertolotti (1990) avoids this difficulty by using a streamfunction formulation. For compressible PSE the resulting equations are hyperbolic in the supersonic region and elliptic in the subsonic region. Here the Vigneron technique (Vigneron et al. 1978) can be used to suppress the upstream wave propagation in the subsonic portion of the boundary layer.

We have formulated and coded the PSE formulation for a surface (including curvature). Then we verified and validated our code. The basis of validation, or confirming that the equations used to model the physical situation are appropriate, is assumed to be a successful comparison with the few careful, archival experiments available in the literature.

Over the next year, equilibrium effects will be included and the flow over the circular cone investigated using the PSE analysis.

Verification

We consider verification to mean "confirming the accuracy and correctness of the code". There are mainly three sources of error in the abstraction of continuous PDE's to a set of discrete algebraic equations; (1) discretization errors, (2) programming errors (bugs), and (3) computer round-off errors. Of the above three, only programming errors can be completely eliminated. The objective of code verification is then to completely eliminate programming errors and confirm that the accuracy of the discretization used in solving the continuous problem lies within some acceptable tolerance. Aside from specifying single or double precision, the code developer has little control over the computer round-off errors, but this is usually several orders of magnitude smaller than the discretization error and far less than the desired accuracy of the solution.

In this section we address programming and discretization errors. Many methods are discussed in the literature for code verification using grid refinement, comparison with simplified analytical cases, etc. For recent discussions see Roache (1997) and Oberkampf et al. (1995). Specific suggestions for testing a CFD code for the study of transition include (a) grid-refinement studies, (b) solving test problems for which the solution is known, (c) changing the "far-field" boundary locations systematically and re-solving, (d) comparing linear growth rates, neutral points, and eigenfunctions with linear stability theory, (e) running the unsteady code with time-

independent boundary conditions to ensure that the calculations remain steady, and (f) running geometrically unsymmetric codes with symmetric conditions.

In addition to the usual code verification techniques, there is a general method which we used to verify the discretizations and locate programming errors by comparison with "manufactured" analytical (Steinberg & Roache 1985). This method is general in that it can be applied to any system of equations. Although it is an extremely powerful tool, this method has received little acclaimation in the literature.

For clarity the technique is demonstrated on the Poisson equation.

$$Lu \equiv \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = F(x,y) \tag{19}$$

To solve this problem we discretize the operator L using some appropriate approximation (finite differences, spectral, etc.). In general, the exact solution is not available. Therefore, for verification purposes, we *force* the solution to (19) to be some combination of analytical functions with nontrivial derivatives. For example, we might consider the system $g \equiv Lv = 5e^{3y}\sin(2x)$, which has an analytical solution $v = e^{3y}\sin(2x)$. The exact solution can then be compared with the computed solution. Of course, manufactured solutions should be chosen with topological qualities similar to those anticipated for the solution to the "real" problem (e.g. gradients close to the wall). Proper choice for the manufactured solutions also allows the discretization of the boundary conditions to be verified. For large systems of equations a symbol manipulator is recommended for computing g. If a bug occurs, zeroing the coefficients of some terms in equation (16) can help to isolate the bug.

We recommend this method in addition to the other specific suggestions mentioned above for code verification. Code validation is discussed in the next Section.

Validation

To date the PSE have been applied to a variety of 2- and 3-D flow situations and are generally regarded as appropriate for convectively unstable flows (Haynes & Reed 1996; Schrauf et al. 1995; Stuckert et al. 1994; Wang et al. 1994; Stuckert et al. 1993; Herbert & Lin 1993; Herbert 1994; Malik & Li 1993; Bertolotti et al. 1992; Chang et al. 1991; Bertolotti 1990).

Bertolotti et al. (1992) verified the PSE approach for T-S (two-dimensional) disturbances in a Blasius boundary layer by comparison with the DNS results of Bayliss et al. (1986). For this nonlinear case they compared not only the growth rates, but also the mode shapes of the harmonics and found excellent agreement. Three-dimensional nonlinear PSE stability results were compared with the experimental results of Kachanov & Levchenko (1984), but only qualitative agreement

was achieved. The differences are attributed to virtual leading-edge and slight pressure-gradient effects in the experiment. Comparison of the same PSE results with DNS results of Fasel et al. (1990) and Crouch (1988) show better agreement. The experimental results of Cornelius (1985) for K-type transition are compared with PSE results and qualitative agreement is found.

All of the above results are on a flat plate. The only available experiments against which to validate our 3-D curved-surface code are those of Reibert et al. (1996) on an NLF(2)-0415 swept airfoil. The nonlinear PSE results include curvature effects. It is clear that the linear theories fail to accurately predict the transitional flow for this situation. Studying a comparison of the experimental and computational disturbance mode shapes, we demonstrated that the nonlinear PSE does an excellent job of capturing the detailed profiles. See Haynes & Reed (1996).

Global Eigenvalue Solver

To generate initial conditions for the nonlinear PSE code, we have also developed a global eigenvalue solver to predict which disturbances are most likely to break down to turbulence. We apply this code to the results of the basic-state code, and then apply the PSE to predict transition location.

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4. Personnel

The principal investigator for this work is Helen L. Reed. She received her Ph.D. in Engineering Mechanics in 1981 from Virginia Polytechnic Institute & State University and joined the faculty at Stanford University in September 1982. In the Fall of 1985, she began her appointment as Associate Professor at Arizona State University (ASU) and was promoted to Full Professor in July 1992. From August 1993-96, she served as Director of the ASU Aerospace Research Center and on December 1, 1994, she was named Associate Director of the ASU NASA Space Grant Program. She also worked at NASA-Langley in the Aeronautical Systems Division and at Sandia Laboratories in the Applied Mathematics Division. Her research interests include computational fluid mechanics, boundary-layer transition, and flow control; low-cost space experimentation, satellite design, and launch systems; alternative-fuel transportation; enabling technologies for micro aerial vehicles; and student-designed vehicles. Recent work includes ASUSat 1, 10-pound satellite designed, built, tested, and tracked by ASU students for low-cost Earth imagery, experimental verification of composite-material models, technology demonstration of student-designed systems, boards, and sensors, and provision of audio transponder for amateur radio operators; student design, fabrication, test, and operation of human-powered moon buggy, solar and electric cars, and micro aerial vehicles; design of low-cost launch system Intrepid; Navier-Stokes simulations of boundary-layer receptivity to freestream sound; and Parabolized-Stability-Equation simulations of 3-D hypersonic boundary layers. She is a past Member of the National Academy of Sciences/National Research Council Aerodynamics Panel (1990-92); a past Member of the NASA Federal Laboratory Review Task Force (1994-95); a past Member of the AIAA Fluid Dynamics Technical Committee (1984-89); a past Member of the Board of Directors of the Society of Engineering Science (1993-95); a past Member of the NASA Computational Aerosciences Review and Planning Team (1994); the past Chair of the Fluid Mechanics Committee of the Applied Mechanics Division of ASME (1993-96); a Fellow of the American Society of Mechanical Engineers (since 1997); an Associate Fellow of the American Institute of Aeronautics & Astronautics (since 1990); a Member of the Executive Committe of the American Physical Society/Division of Fluid Dynamics (1996-98); a Member of the U.S. National Transition Study Group (since 1984); the Originator of the Gallery of Fluid Motions of the American Physical Society (since 1983); a Member of the NASA Headquarters Aeronautics Advisory Committee (AAC), recently renamed Aeronautics and Space Transportation Technology Advisory Committee (ASTTAC) (1994-97); the first woman Member of the NATO/AGARD Fluid Dynamics Panel (1995-97); a Member of the NASA Headquarters AAC Task Force on University Strategy (1995-97); and the Associate Editor of the Annual Review of Fluid Mechanics (since 1986). At ASU, she completed Leadership Academy in 1993-94; received the 1993-94 Undergraduate Teaching Excellence Award in the College of Engineering & Applied Sciences, the 1994-95 Outstanding

Graduate Faculty Mentor Award from the Graduate College, the 1995 Bronze (ASU) President's Medal for Team Excellence, and the 1996 Distinguished Mentor of Women Award from the Faculty Women's Association; and is a member of the ASU team named as 1997 Finalist in the Boeing Outstanding Educator Award competition.

The PhD student working on this project was Mr. Ian Lyttle. He will receive his Ph.D in Aerospace Engineering from Arizona State University next Summer 1998.

Appendix A

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Education:

Ph.D., Engineering Mechanics, Virginia Polytechnic Institute & State University, December 1981
M.S., Engineering Mechanics, Virginia Polytechnic Institute & State University, June 1980
A.B. in Mathematics, Goucher College, May 1977

Professional Experience:

December 1994-Present	Associate Director, NASA Space Grant Program, ASU
July 1992-Present	Professor, Mechanical & Aerospace Engineering, ASU
August 1993-August 1996	Director, Aerospace Research Center (ARC), Arizona State University (ASU)
August 1985-June 1992	Associate Professor, Mechanical & Aerospace Engineering, ASU
September 1982-August 1985	Assistant Professor, Mechanical Engineering, Stanford University
June 1977-December 1981	Aerospace Technologist, NASA/Langley Research Center

Awards and Recognitions:

1997	Fellow, American Society of Mechanical Engineers, July
1997	1st Place in Student Competition at 11th AIAA/USU Small Satellite Conference, Faculty Advisor
1997	Member of ASU Team selected as Finalist for Boeing Outstanding Educator Award
1997	Invited for Poster Session on Capitol Hill sponsored by Council on Undergraduate Research (ASUSat 1), April 10
1997	2nd in "Best Overall Design" (Moon Devil III), 4th Moon Buggy Race, US Space & Rocket Center, Huntsville
1997	Article (ASUSat 1), *PRISM* (from American Society of Engineering Education), April
1996	Cover story (ASUSat 1), *Graduating Engineer* (from Peterson's Magazine Group), Volume 18, Issue 1
1996	"Best Overall Design" and 2nd in Race (Moon Devil II), 3rd Moon Buggy Race, US Space & Rocket Center, Huntsville
1996	Distinguished Mentor of Women Award, Faculty Women's Association, ASU
1995	1st Place in Student Competition at 9th AIAA/USU Small Satellite Conference, Faculty Advisor
1995	Bronze (ASU) President's Medal for Team Excellence
1994-95	Outstanding Faculty Graduate Mentor Award from the Graduate College, ASU
1994	1st Place in Student Competition at 8th AIAA/USU Small Satellite Conference, Faculty Advisor
1993-94	Undergraduate Teaching Award from College of Engineering & Applied Sciences, ASU
1988-89	Professor of the Year, Pi Tau Sigma, ASU
1988	AIAA Excellence in Teaching Award, ASU
1991	Faculty Awards for Women in Science and Engineering, National Science Foundation
1984	Presidential Young Investigator Award, National Science Foundation
1978	Outstanding Achievement Award from NASA/Langley Research Center
1976	Outstanding Summer Employee Award from NASA/Langley Research Center

Service:

Member, NASA Federal Laboratory Review Task Force, NASA Advisory Council (NAC), September 94-March 95
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Member, NASA Aeronautics Advisory Committee (AAC), December 1994-1996
Member, NATO/AGARD Fluid Dynamics Panel, 1995-1998
Member, NASA Aeronautics Advisory Committee Task Force on University Strategy, 1995-1997
Member, Executive Committee of the American Physical Society/Division of Fluid Dynamics, 1996-1999
Member, Board of Directors of the Society of Engineering Science, 1993-1995
Member, U.S. National Transition Study Group, 1984-Present

Member, NSF Presidential Young Investigator Workshop on U.S. Engineering, Mathematics, and Science Education for the Year 2010 and Beyond, November 4-6, 1990

Member, National Academy of Sciences/National Research Council Aerodynamics Panel which is a part of the Committee on Aeronautical Technologies of the Aeronautics and Space Engineering Board, November 1990-March 1992

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Research Interests:

Computational fluid mechanics, boundary-layer transition, and flow control; low-cost space experimentation, satellite design, and launch systems; alternative-fuel transportation; enabling technologies for micro aerial vehicles; and student-designed vehicles. Recent work includes ASUSat 1, 10-pound satellite designed, built, tested, and tracked by ASU students for low-cost Earth imagery, experimental verification of composite-material models, technology demonstration of student-designed systems, boards, and sensors, and provision of audio transponder for amateur radio operators; student design, fabrication, test, and operation of human-powered moon buggy, solar and electric cars, and micro aerial vehicles; design of low-cost launch system Intrepid; Navier-Stokes simulations of boundary-layer receptivity to freestream sound; and Parabolized-Stability-Equation simulations of 3-D hypersonic boundary layers.

Publications:

"Flow over Plates with Suction through Porous Strips," Nayfeh, Reed, Ragab, *AIAA J.* 20, 5, 587, 1982.

"Stability of Flow over Axisymmetric Bodies with Porous Suction Strips," Nayfeh, Reed, *Phys. Fluids*, 28, 10, 2990, 1985.

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"ASUSat 1: A Low-Cost Amateur Radio Nanosatellite," Ferring, Rademacher, McAllister, Friedman, Reed, Puig-Suari, *AMSAT J.*, 20, 3, 12-17, 1997.

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Fellow, American Society of Mechanical Engineers (ASME)

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Member, AMSAT (Amateur Satellite Organization)

Member, American Physical Society (APS)

Member, American Society for Engineering Education (ASEE)

Member, Association for Unmanned Vehicle Systems International (AUVSI)

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